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U. S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

Aviation Medical Acceleration Laboratory

NADC-MA-6110

27 November 1961

Control Performance Under Acceleration
With Side-Arm Attitude Controllers

Bureau of Medicine and Surgery
Task MR005.13-0005.6 Report No. 11

Bureau of Naval Weapons
WepTask No. RAE 20J 031/2021/R005 01 003
Problem Assignment No. J04AE13-7

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SUMMARY

This paper presents some procedures, data, and conclusions based on several closed-loop centrifuge experiments in which side-arm controllers were used by pilots to perform specific control tasks. Under certain conditions the pilots could perform as well in adverse acceleration fields as they could statically, even though they were exerting much more physical effort and psychological concentration, and they were enduring visual impairment, chest pains, breathing difficulties, and other stressful effects of acceleration. The pilots demonstrated a remarkable ability to adapt to physiologically severe acceleration environments, and they maintained control performance within acceleration time history profiles which contained vectors with amplitudes as high as $+15 G_x$, $-7 G_x$, and $+7 G_z$. Some closed-loop human centrifuge simulations were conducted which provided human factors data which may have application to the design and evaluation of side-arm controllers for use within proposed space vehicles.

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Acknowledgment and appreciation are given to the engineering personnel from the High Speed Flight Center, the Langley Research Center, and the Ames Research Center of the National Aeronautics and Space Administration; the pilots from the USAF, USN, and USMC who served as subjects; and the engineering and medical personnel of the Aeronautical Computer Laboratory and the Aviation Medical Acceleration Laboratory of the U. S. Naval Air Development Center who participated in these studies.

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LIST OF SYMBOLS

G	gravitational constant, 32.2 ft/sec^2
$+G_x$	acceleration along the transverse (ventral-dorsal) axis of the pilot's body, chest-to-back
$-G_x$	acceleration along the transverse (dorsal-ventral) axis of the pilot's body, back-to-chest
$+G_z$	acceleration along the longitudinal (spinal cord) axis of the pilot's body, head-to-foot
A	an acceleration vector along an axis of the pilot's body
δ_n	error in nozzle deflection angle
ϕ	error in roll
ψ	error in yaw
$\gamma_p - \gamma_a$	error in flight-path angle
$\omega_n^2, 2\zeta\omega_n$	aerodynamic stability and damping, respectively
V	velocity, ft/sec
\bar{q}	dynamic pressure, lb/sq ft
h	altitude, ft
γ	flight-path angle, deg
e	angle-of-attack error
P	period
ζ	damping ratio
α	angle of attack
ϵ	vertical tracking error
$\int \theta_i^2 dt$	integral of target input squared
$P.E.$	$\frac{100 \int (\theta_i^2 - \epsilon^2) dt}{\int \theta_i^2 dt}$

INTRODUCTION

Acceleration stress characteristics of some proposed space vehicles may temporarily distort human anatomy, modify human physiology, and place limits on human performance capabilities (1, 2, 3, 4, 5, 6, 7). Although there has been extensive research on the physiological tolerance limits for a wide variety of acceleration profiles, there are few experimental reports which indicate the effects of acceleration on the ability of a human pilot to operate specific control devices under conditions in which he is trying to accomplish specific launch or reentry piloting tasks (8, 9, 10). Explorations concerning the capabilities of the human pilot for serving a primary piloting role in certain maneuvers, and as a back-up role in emergency situations have included considerations of various devices designed to compensate for the effects of acceleration on the abilities of the pilot during acceleration stress (11, 12, 13, 14, 15, 16). The conventional center control stick, for example, does not permit maximum piloting performance in certain types of acceleration fields, and many test pilots and engineers have proposed other types of controllers designed to permit the pilot to maintain more effective control of his vehicle in adverse environments.

One general class of controllers, designated as side-arm controllers, has recently received extensive test by pilots who flew specific piloting tasks within static simulators, centrifuge acceleration environments, and aircraft. The purpose of this report is to present some recent experiments in which the ability of pilots to use side-arm controllers was studied under laboratory conditions within centrifuge acceleration environments, some of which simulated time history profiles of proposed space vehicles. The emphasis of this paper is on human factors data which may be of interest to engineers who are concerned with problems in the design and evaluation of side-arm controllers. Emphasis is given to methods of test and evaluation, the stresses perceived by pilots, and some results of tests conducted on representative types of controllers. Although details of flight simulation and characteristics of simulated vehicles cannot be reported in this paper, it is believed that some of the human factors information may be of interest.

APPARATUS AND EXPERIMENTAL METHODS

The primary research apparatus was the human centrifuge, shown in Figure 1, which provides the capability for exposing a human subject positioned in the gondola to many varieties of acceleration fields whose characteristics may vary along dimensions such as direction, amplitude, duration, rate of onset, and complexity. Control of these accelerations is

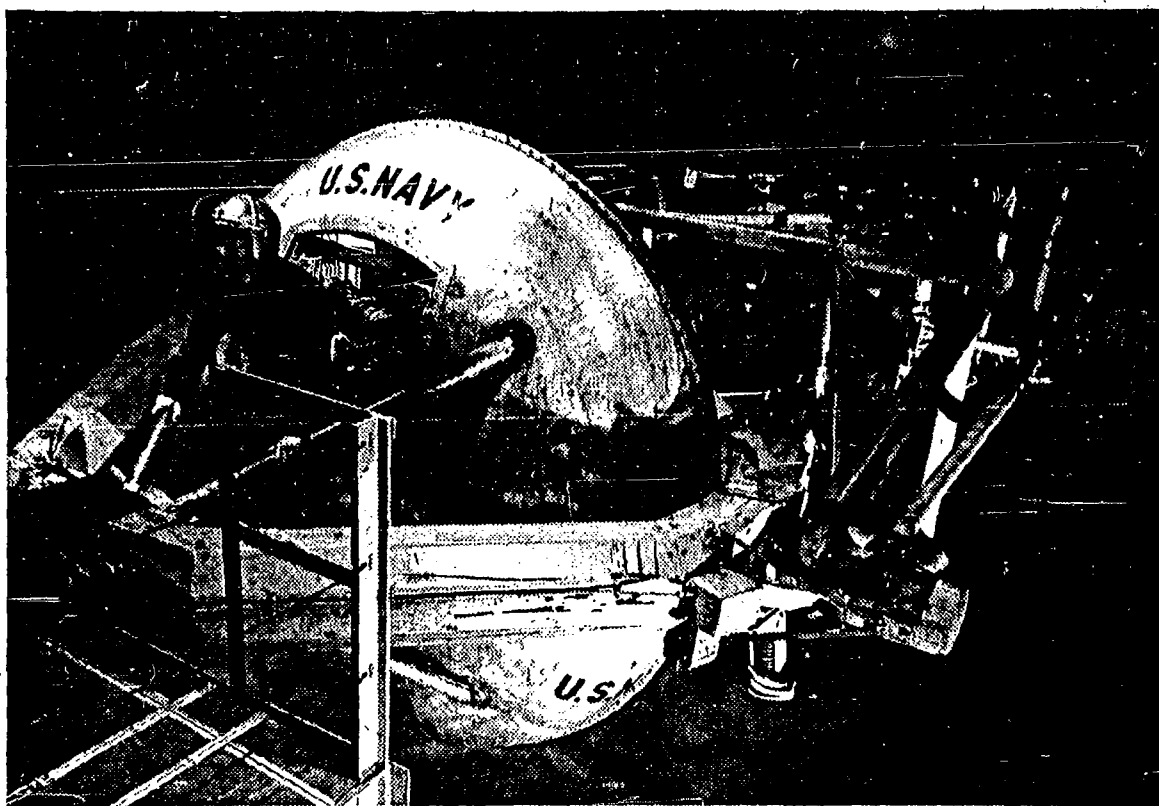


Figure 1. The human centrifuge, located at the Aviation Medical Acceleration Laboratory, U. S. Naval Air Development Center, Johnsville, Pa. The figure shows the housing for the 4000 h.p. direct current motor, the 50-foot centrifuge arm, the gondola suspended in a double gimbal system at the end of the arm, and the pilot loading platform.

obtained by applying suitable signal inputs to the servo systems controlling the radial acceleration of the centrifuge arm and the motion and positions of the two gimbals. The centrifuge is supplemented by computer facilities which enable the simulation of specific vehicle characteristics (17, 18). Linear acceleration is simulated on the centrifuge by using angular velocity. Three linear acceleration components of flight are simulated continuously, and emphasis is placed on these. As far as the pilot is concerned, it is convenient to consider the resolution of the acceleration vectors in terms of three components, A_x (acceleration along the pilot's dorsal-ventral axis), A_y (acceleration along the pilot's lateral axis), and A_z (acceleration along the pilot's body axis). Since the relative orientation of the pilot with respect to his resultant acceleration vector can be continually controlled, any given vector may be positive, negative, or zero, depending upon the position of the pilot with reference to his acceleration vectors.

This apparatus was used in three studies discussed in this paper, each of which was, in part, concerned with the use of side-arm controllers: the boost-orbital centrifuge simulation program, the high drag reentry centrifuge simulation program, and a centrifuge study of piloting performance in sustained acceleration environments.* References 15, 16, 17, 21, and 22 present portions of the first two programs. The instrumentation and conduct of the research were accomplished jointly by the National Aeronautics and Space Administration (NASA), and the Aviation Medical Acceleration Laboratory, and the Aeronautical Computer Laboratory of the U. S. Naval Air Development Center, Johnsville, Pa. In these investigations, the pilot sat in the gondola facing his instrument panel and operated his controller to execute his flight mission. He "flew" the centrifuge by operating his controller in response to information presented on the flight instruments which were mounted on his panel within the gondola. Figure 2 presents a diagram of this procedure. The pilot's control movements are fed into the analog computer system and these, along with the aerodynamic equations and vehicle characteristics stored in the computer, are converted into signals which, through a coordinate transformation system and time compensating network, drive the main arm and two gimbals of the centrifuge and also the instruments on the pilot's display panel. Thus, along certain programmed dimensions, the pilot receives an approximation of the accelerations which he would receive in the actual vehicle under the conditions assumed by the equations and the vehicle dynamics stored in the computer.

* Cooperative studies conducted with the High Speed Flight Center, NASA, Edwards, California; the Langley Research Center, NASA, Langley Field, Virginia; and the Ames Research Center, NASA, Moffett Field, California.

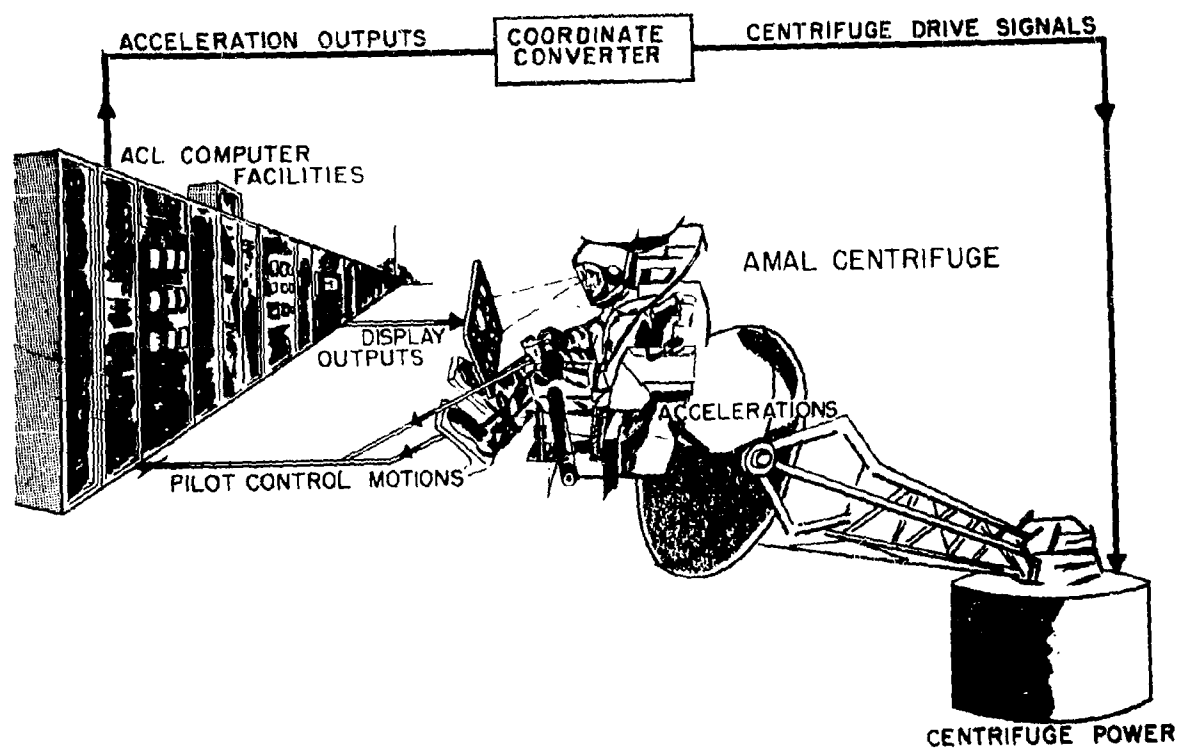


Figure 2. General diagram showing closed-loop pilot-computer centrifuge control procedure.

A total of 24 pilots from NASA, USAF, USN, and USMC were selected and trained on specific flight problems programmed in static simulators at NASA prior to participating in these centrifuge experiments.

Figures 3 through 8 show the general construction, shape, and model of operation for the controllers used in these experiments. For convenience in future reference, each controller is assigned a number. Figure 3 shows Type I, a three-axis electronic controller developed by the NASA High Speed Flight Center (16). The pilot uses his right hand in applying pitch, roll, and yaw from the grip. All pivots are passed through the center of the wrist. Trim in pitch was also available to the pilot. In some experimental work, the yaw axis was locked, and the pilot used "toe pedals" for this mode of control. Under this latter condition, this controller is referred to as Type III. Figure 4 shows another type of three-axis controller, referred to as Type II. This controller, provided by NASA, has yaw, pitch, and roll control from the grip. However, the pitch axis is near the wrist, roll lies below the arm support, and the yaw axis is through the grip, and is controlled by twisting the grip. This controller is shown in a modified condition with additional counterweights to improve static balance. Figure 5 shows a two-axis controller, referred to as Type IV. This controller (5) was provided by NASA. Yaw control is provided via "toe pedals" (not shown). A two-axis "pencil" controller is shown in Figure 6, as Type V. It consists of a small box from which a slender rod topped by a small plastic ball may be moved for pitch and roll control (15, 19). Yaw control is provided by "toe pedals". Figure 7 shows the two-axis force stick controller, referred to as Type VI. It consists of a vertical grip having negligible displacement. Strain gauge sensors measure the magnitude of applied pitch and roll forces. "Toe pedals" were used for yaw control. Figure 8 shows a modification of the two-axis force stick. Referred to as Type VII, it contains a small rod with a ball on top which the pilot holds to control for pitch and roll.

SUCCESSIVELY HIGHER STAGING ACCELERATIONS

An attempt was made to isolate the effects of acceleration on the ability of pilots to use a specific three-axis side-arm controller (Type I) under conditions in which the same launch problem was repeated at successively higher staging accelerations. Control performance was studied during the first 1 1/2 stages of a four-stage launch of an orbital rocket which was simulated on the centrifuge. The task of the pilot was to "fly" a programmed flight path, under specific conditions of damping and aerodynamic stability, while being subjected to closed-loop controlled $+A_x$ acceleration profiles whose peaks were 1, 3, 6, 9, 12 and 15 G. Figure 9 shows these acceleration profiles. Three levels of stability and damping were studied within

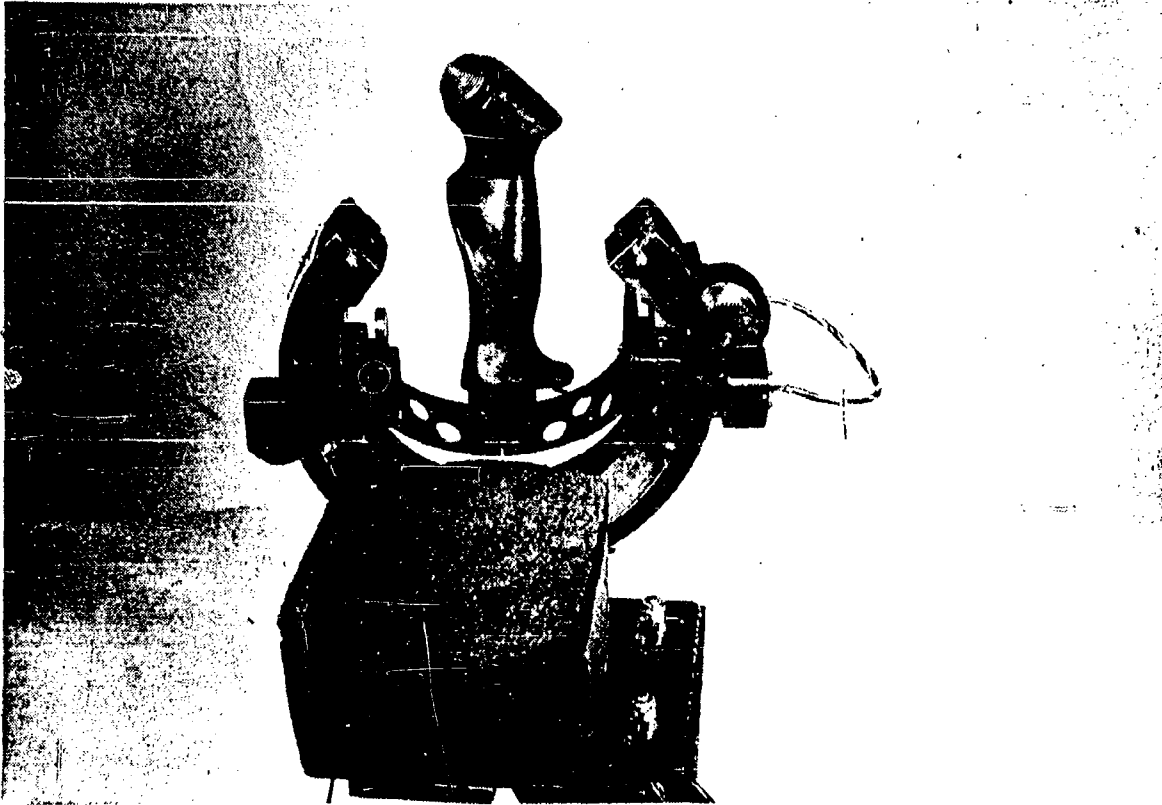


Figure 3. Type I controller; A three-axis side-arm controller developed by the NASA High Speed Flight Center. The sponge rubber at the base was added at wrist and forearm support during acceleration studies on the centrifuge. In some experiments, the yaw axis was locked, and operated with toe pedals. In this condition, with only pitch and roll operative with the right hand, this controller is referred to as Type III.

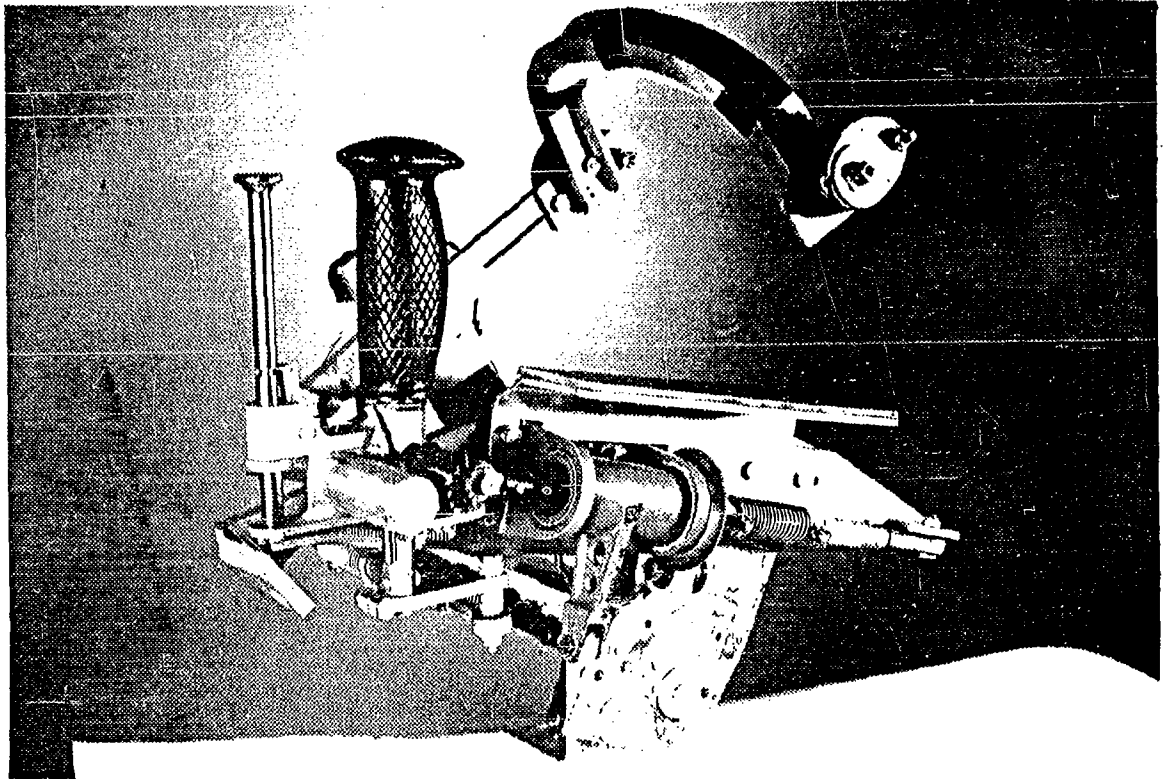


Figure 4. Type II controller: A three-axis controller provided by NASA. The counterweights were added to provide additional balance during centrifuge tests.

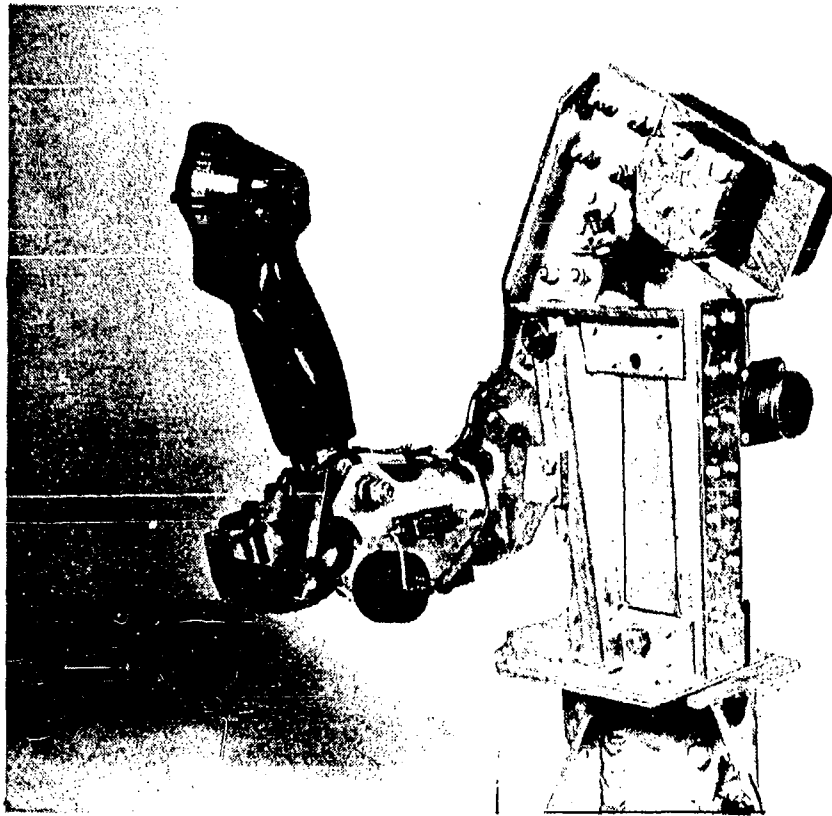


Figure 5. Type IV controller: A two-axis controller provided by NASA.

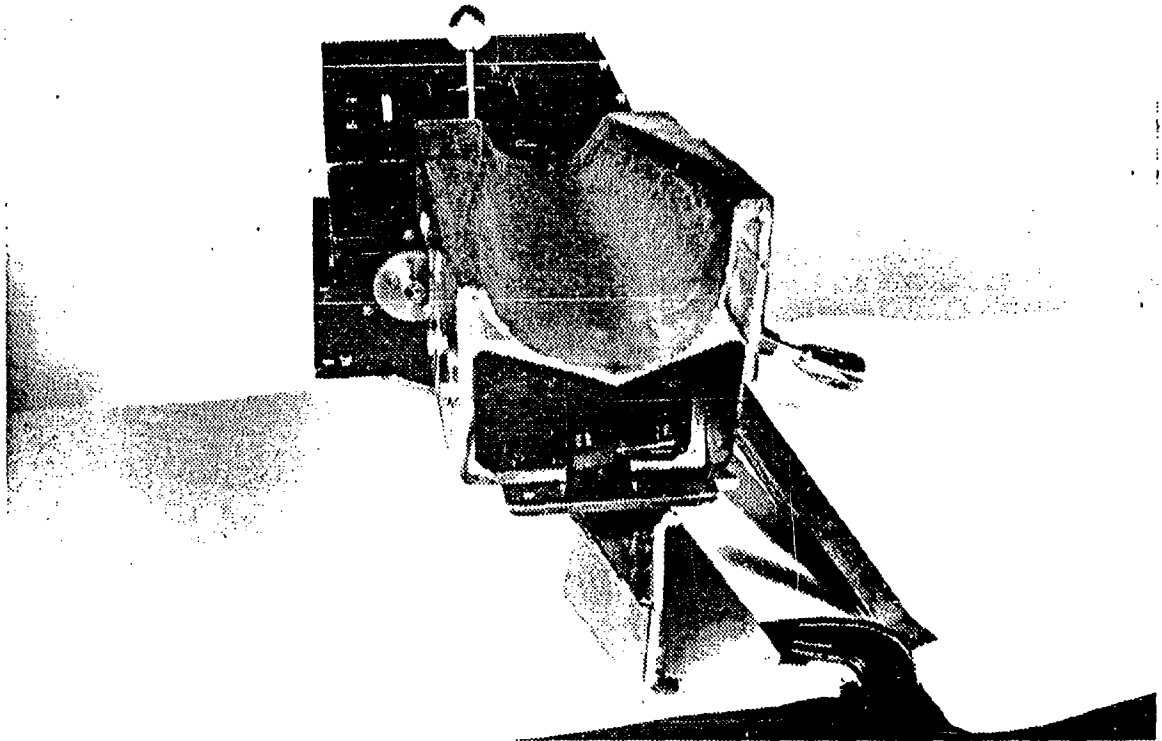


Figure 6. Type V controller: A two-axis pencil controller, sometimes called the finger-tip control stick, developed by the NASA Langley Research Center.

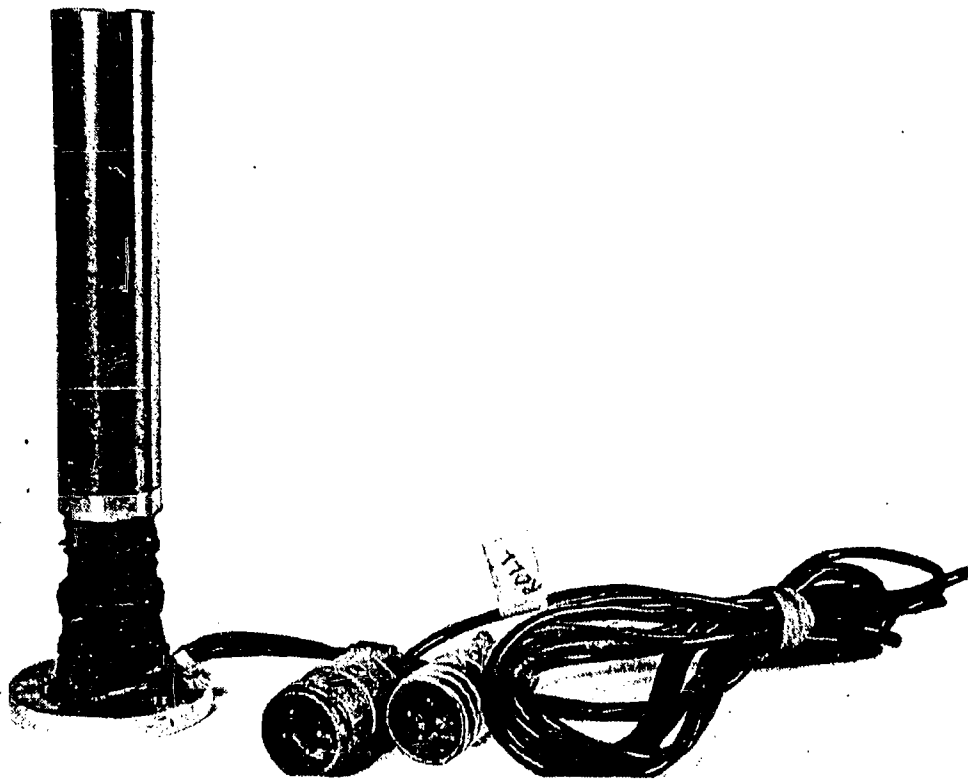


Figure 7. Type VI controller: A two-axis force sensitive controller, developed by NASA. This controller consists of a vertical grip having negligible displacement with strain gauge sensors to measure the magnitude of applied pitch and roll forces.

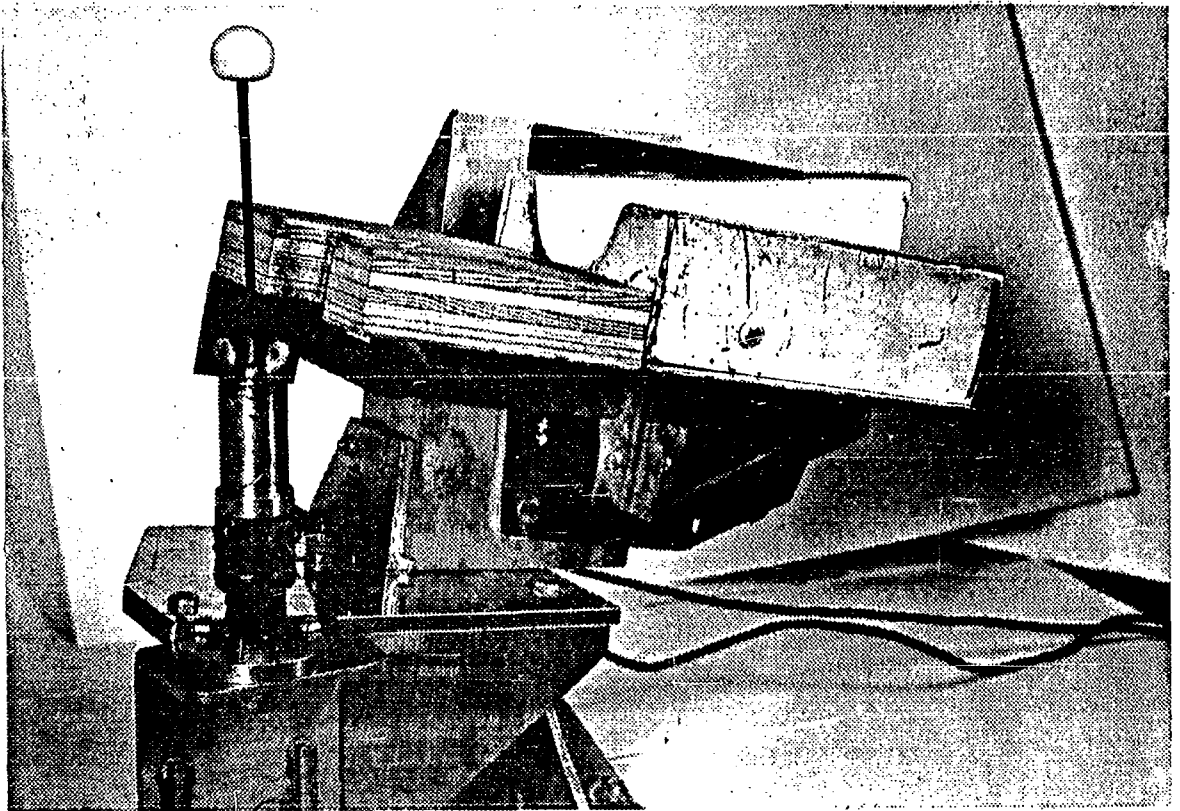


Figure 8. Type VII controller: A two-axis force sensitive controller, provided by NASA. This controller is a modification of Type VI with the addition of a small ball on the end of a rod extended from the top of the vertical grip.

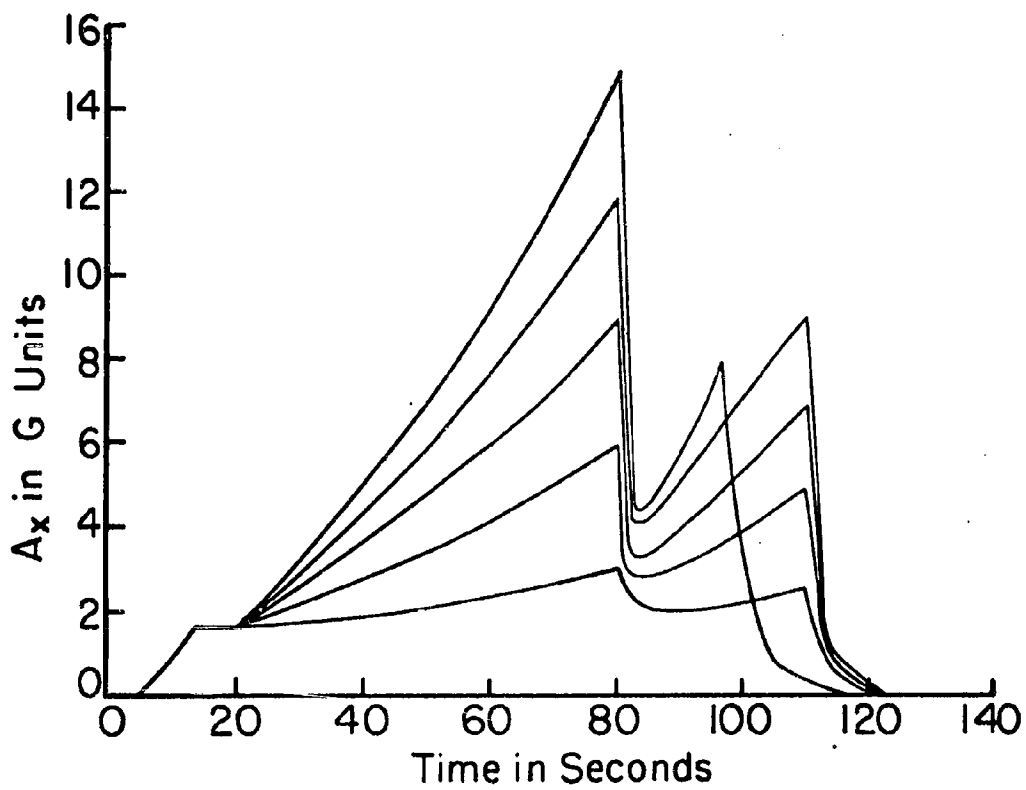


Figure 9. Acceleration time histories used in study of side-arm control performance during staging simulations.

each of these acceleration fields. Approximately 40 quantities (including engineering, physiological, and performance measurements) were recorded continuously during these staging runs.

Since ability to utilize a controller under acceleration is so dependent upon the way in which the pilot is restrained within the acceleration environment and upon the effectiveness of his G-protection devices, the most advanced restraint equipment possible was developed. A typical installation of the pilot and his associated restraint and control equipment is shown in Figure 10, which shows the individually form-fitted contour couch and restraints for the head, chest, and legs. The seat-back angle and the leg-support angle to the transverse-acceleration vector (A_x) was 75 degrees. This angle was selected to provide a compromise between chest pain and vision impairment. To relieve the pressure of the thigh weight on the pelvis, and also to provide an acceptable seat for either the upright or supine position, seat angularity was molded at 97 degrees. The arm-rest to back angle was 110 degrees.

The flight problem was presented on the instrument panel shown in Figure 11. The primary instruments were angle of attack, nozzle position, the artificial horizon, and the programmer. The program guidance during staging was presented to the pilot as a flight path error, displayed on an ILS instrument. The piloting task was to maintain zero flight path error, and zero error in pitch, roll, and yaw axes. Longitudinal control and lateral-directional control were required. Other instruments available to the pilot (see Figure 11) were side-slip, vertical pitch angle, yaw angle, angle of bank, normal acceleration, transverse acceleration, inertial altitude, inertial velocity, inertial rate-of-climb, booster-stage firing, booster burning time remaining, and warning indications for pitch-damper failure, 5 seconds before burning time, pitch-stabilization failure, and pitch-program failure. The centrifuge operation was closed-loop in the A_x and in the A_z acceleration. Accelerations in A_y were programmed to zero. The primary subjects in the experiment were seven highly trained pilots who had completed a static simulation program prior to arriving at the human centrifuge facility.

An analysis of the recordings, ratings, and piloting interview data from this experiment indicated that up through $9 G_x$, most of the pilots did as well or better in performing the flight problem under conditions of acceleration as they did statically. On profiles whose peaks were $12 G_x$, individual records of piloting performance showed impairment on some control quantities. This appeared to be largely attributed to visual problems and was not shown in all cases. Figure 12 has been prepared to summarize piloting scores on the



Figure 10. Restraint system used in centrifuge study of piloting performance during simulations. The pilot was restrained in an individually molded contour couch designed to afford maximum support and comfort and minimum interference with the piloting task. The pilot's right hand operated Type I controller, and his left hand operated a problem termination switch and a "stop-the-run" switch. The pilot's head, chest, and legs were secured to the couch and its associated strong-back.

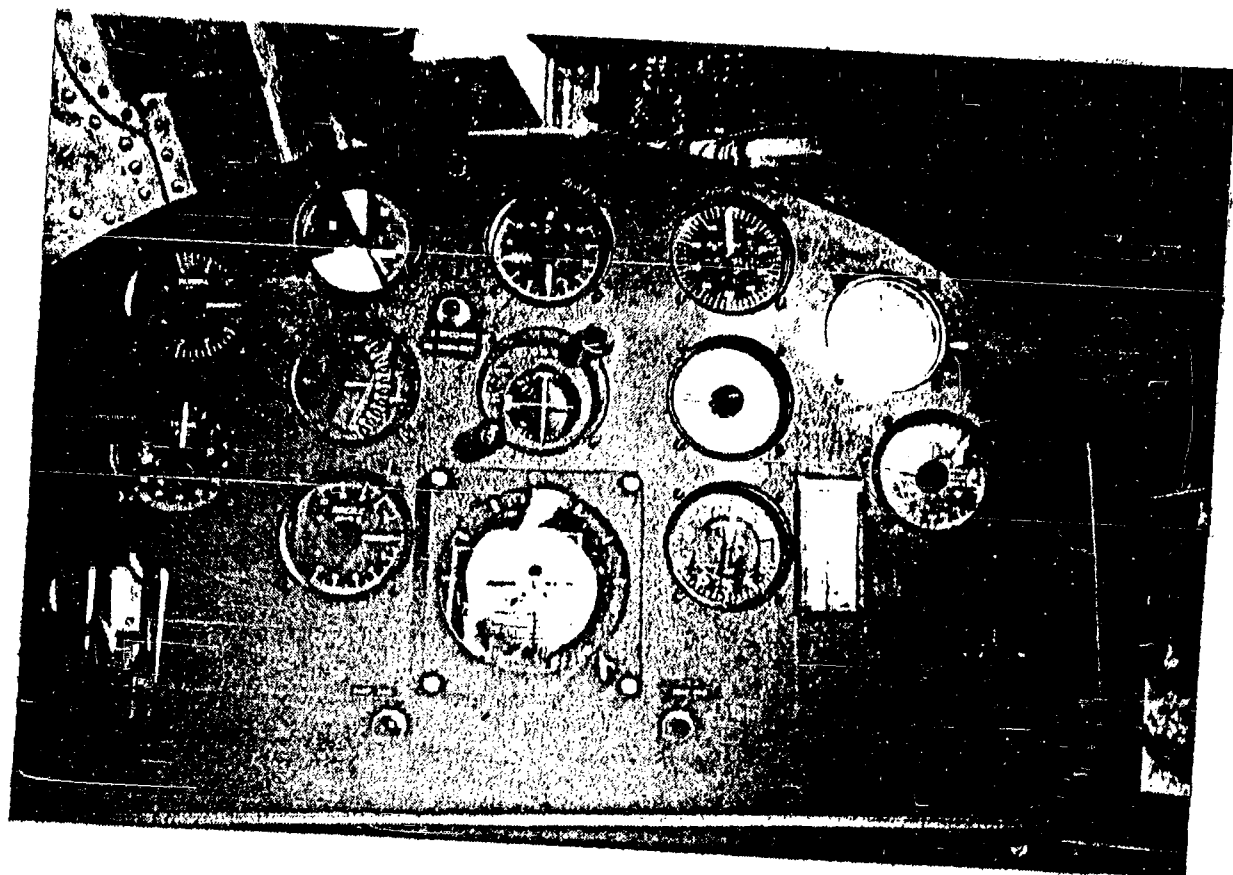


Figure 11. Panel and instruments used in boost-orbital centrifuge simulation program. The instruments show angle of attack, rocket nozzle angle, flight path error, altitude, transverse G, normal G, sideslip, pitch angle, roll angle, yaw angle, inertial altitude, inertial velocity, inertial rate-of-climb, booster-stage firing, booster burning time remaining, pitch-damper failure, pitch-stabilization failure, pitch-program failure, and 5 seconds before burning time.

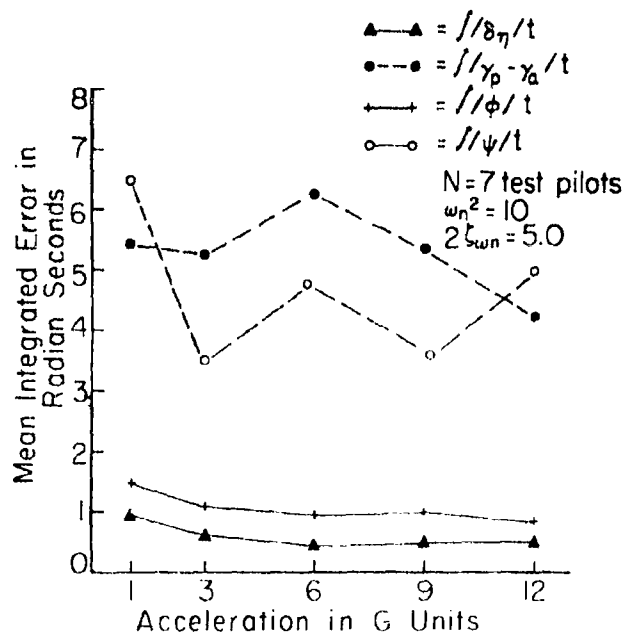


Figure 12. Mean error performance scores for 7 pilots who "flew" a staging control task through peak centrifuge acceleration levels of 1, 3, 6, 9, and 12 G_x .

main control quantities. These are expressed as mean integrated error in radian seconds for flight path, nozzle deflection angle in pitch, roll error, and yaw error, for the 7 pilots at accelerations of 1, 3, 6, 9, and 12 G_x peak values. No significant decrement in control performance is shown on the graph. Another analysis of altitude and angle of attack quantities showed no significant differences between control performance under static and dynamic conditions. The simulation during these runs was for vehicles which had good aerodynamic stability and damping. In simulations characterized by more instability and poor damping, there were suggestions of performance impairment, especially at 12 G. Under these conditions, individual differences among pilots in performing the control tasks were increased.

The conditions under which some of the pilots performed their control task at 15 G were slightly different from those completed at 3, 6, 9, and 12 G. Therefore, the results of the 15 G runs and their corresponding control runs (static, 1 G) are plotted separately. Figure 13 summarizes these results for 2 pilots. The piloting task was accomplished, although performance impairment was shown. The main difficulty was an almost complete inability to see the panel instruments during the peak of the 15 G runs. Breathing was very difficult, and there was chest pain during these runs; however, despite these factors, the pilots were able to maintain control over their simulated vehicles. The greatest error was in a secondary quantity, yaw angle error, which was nearly 5 times as great at 15 G as at 1 G. Errors in the other three quantities were much less, although the same general trend was shown. Considering the physiological stress, as indicated by electrocardiographic recordings, breathing and galvanic skin response records, and visual impairment, discomfort and pain, these pilots demonstrated remarkable performance. This was probably due to (a) the high degree of motivation, training, and experience characteristic of the pilots, (b) the superior support and restraint system, and (c) the balanced side-arm controller and its associated design characteristics.

ACCELERATIONS DURING COMPLETE LAUNCH

Similar results have been obtained on more complicated flight profiles in which the pilots flew complete 2-stage and 4-stage launch simulations. Figure 14 presents acceleration, velocity, dynamic pressure, altitude, and flight path angles for the two-stage launch as simulated on the centrifuge. Figure 15 presents similar flight profiles for the four-stage launch simulation. In these simulations, four degrees of control task difficulty were tested. Difficulty varied according to vehicle stability, damping, and type of guidance. The problem was to determine whether the acceleration

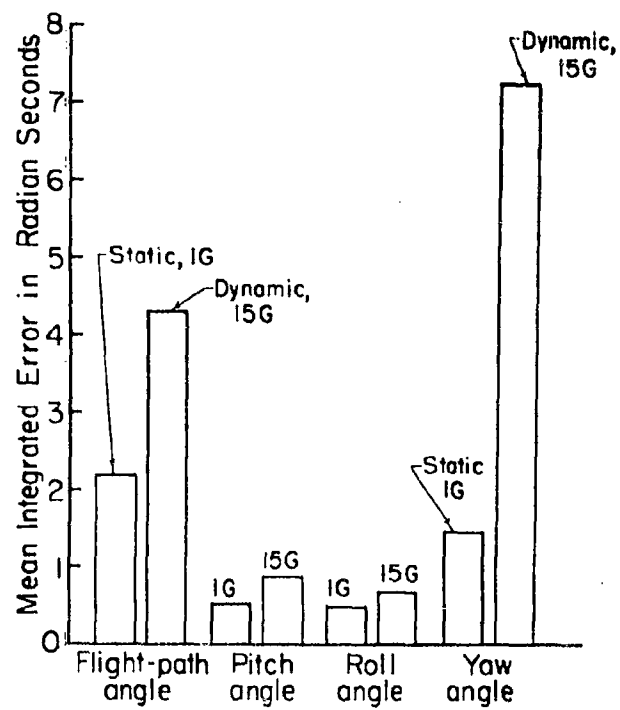


Figure 13. Error performance during static and 15 G_x staging centrifuge runs.

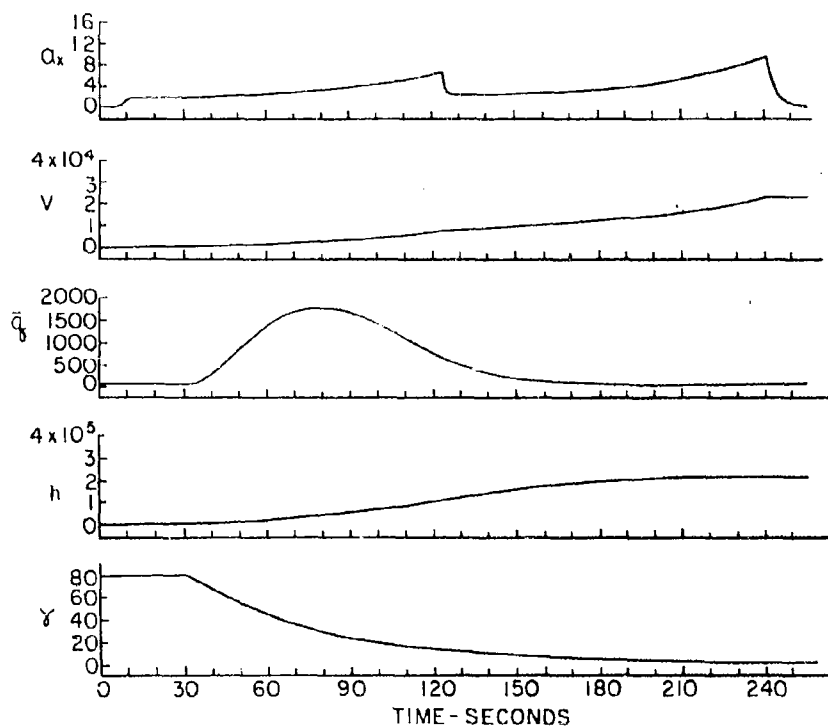


Figure 14. Typical time history profiles for two-stage launch simulations.

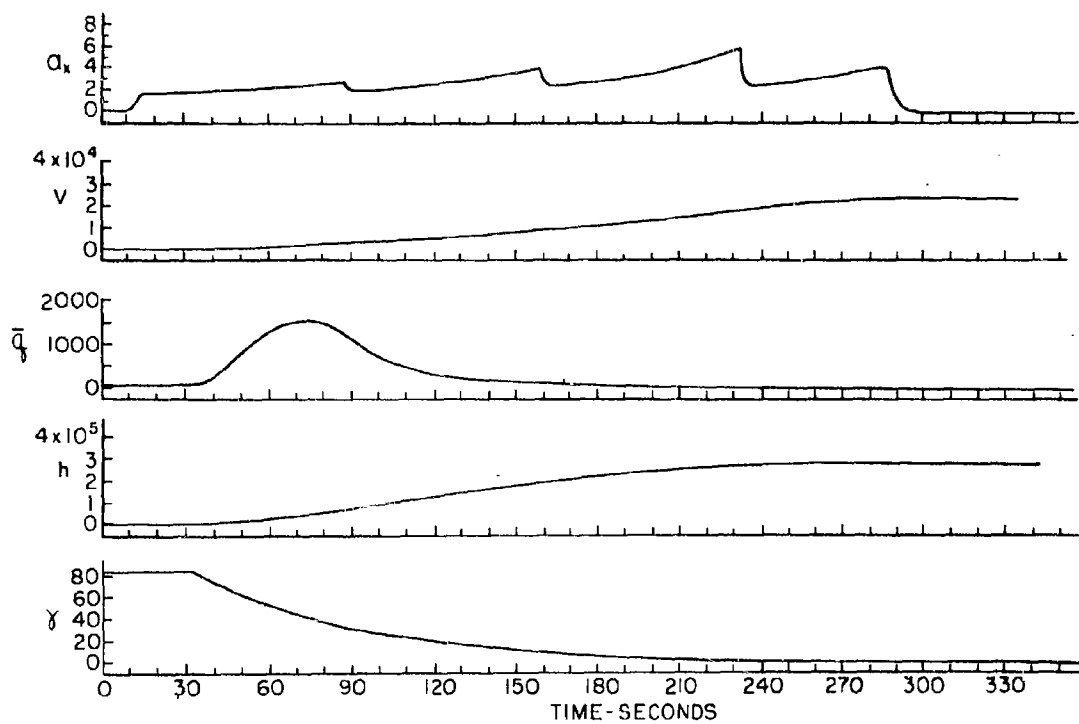


Figure 15. Typical time history profiles for four-stage launch simulations.

environment typical of the 2-stage or the 4-stage launch impaired piloting performance at any of the four difficulty levels. The analysis of this data consisted of comparisons between piloting scores obtained during static runs (e.g., the centrifuge at stand-still) and dynamic runs (e.g., the centrifuge in motion).

The mean error scores obtained by the pilots in maintaining control of flight path angle, nozzle deflection angle in pitch, and bank angle were essentially the same for both static and dynamic conditions. There appeared to be a slight tendency for error in heading to increase, but this was not significant. There appeared to be no effect of acceleration on control of the attitude flight task. Although there were differences in the final velocity achieved by pilots in flying the two-stage and the four-stage simulations, these differences were not attributed to the acceleration variable. In this experiment, there was no conclusive evidence which suggested any significant effects of acceleration on the ability of the pilots to maintain control of the flight problems which had been simulated both dynamically and statically. Despite the effects of acceleration on the physiological behavior of the pilots (as indicated by the respiration, electrocardiographic, movie, and piloting opinion records), the pilots were capable of performing the control tasks as well dynamically as statically. Any differences which were observed in performance were attributed to variables such as task difficulty and number of stages, rather than to acceleration. In order to clarify this point, to summarize the effects of acceleration as perceived by the pilots, and to contrast these effects with the results of the performance analysis, a content analysis of piloting opinion and interview data was conducted, the results of which are presented below.

PERCEPTIONS REPORTED AT DIFFERENT G AMPLITUDES

During and between runs, the pilots were asked a series of standard questions, and they were encouraged to give extensive comments. Also, after each series of runs, the pilots were interviewed in an attempt to obtain further information concerning their perceptions regarding their reactions and performance during acceleration exposures. The study showed that the 3 G staging runs were characterized by a slight difficulty in focusing on the instruments, and a very slight disorientation. These subsided with practice. The 6 G runs were characterized by feelings of tightness in the chest, mildly irritating chest pains, and some observable loss of peripheral vision. Difficulties in breathing and speaking were also reported by the pilot. There was a perceived decrease in the depth of the visual field, and pilots reported that additional effort was necessary in order to scan the panel. Vision tended to settle on two or three instruments, which at times appeared blurred. Some pilots reported an impairment of their ability to focus, and

effort was required to maintain appropriate focus on the instruments. Most of the pilots reported a deterioration in their ability to "fly" the program as accurately under 6 G as they could statically. They reported a tendency to overcontrol. Also, while making roll corrections, they found it difficult to maintain precise pitch control.

At the higher acceleration levels, the intensity of the above effects was reported as increasing as a function of the increased acceleration level. The 9 G runs were characterized by "slight" chest pains, and a sensation of heaviness on the chest and stomach. Breathing was difficult, and required tensing the chest and stomach muscles. Most pilots adopted a technique of small half-breaths. Visual symptoms were slight blurring, a tendency for the eyelids to close over the eyeballs, reduced peripheral vision, and occasional tears. Only a small area around any given instrument could be detected. The amount of piloting concentration required to fly this maneuver was increased over runs made at lower G levels. The pilots reported several items of importance concerning their use of the side-arm controller. The general response of the control system was not as good dynamically as statically. The controller did not appear to react as fast at 9 G as it did during static runs. The movements on the controller appeared to be heavy, requiring more efforts to make control motions. There were reports of difficulty in getting large enough control motions at this acceleration level, and reports that the acceleration tended to pull the control stick down in the pitch mode, requiring effort to stay with the flight program. The pilots found it necessary to keep the arms rigid and the wrists steady. Wrist motions required more effort dynamically than statically, and it was difficult to determine the required amount of rotation necessary beyond the neutral point for control precision. Some difficulty in centering yaw was reported. In general, all pilots reported that their ability to use the controller decreased, and this seemed to be a deterioration in "piloting feel" for determining how much control to put in the deflection force. Some pilots reported an estimated increase in the tendency to make inadvertent control inputs, and there were reports of hesitation to make certain control motions because of the increased possibility of inadvertent control inputs.

At 12 G, difficulty in breathing seemed to be one of the main problems. There was severe pressure and discomfort on the chest, and chest pain was reported by all pilots. These runs were physically tiring. Vision was another primary problem area. Some pilots reported major difficulty in seeing the instruments on the panel. Much loss of peripheral vision occurred, brightness appeared dimmed, there was extreme "fuzziness", and a marked lack of visual acuity, accompanied by some watering of the eyes. The pilots had to strain their eyes in order to maintain focus, and

even instruments which were directly in focus at one instant frequently became blurred the next. Scanning the panel was nearly impossible, except when marked effort was exerted. Individual differences in ability were shown among the pilots in visual characteristics. Effort was required to keep the eyes open. Some pilots reported that it was difficult for them to make control motions, and their ability to coordinate control motions in more than one axis at a time was difficult. The pilots reported that it took almost complete concentration to maintain control at this G level.

Some pilots reported complete impairment of vision at 15 G. Even the staging light, which had been visible at 12 G, was not visible at this high G level. These symptoms were very short in duration, however, so that the pilots were able to "fly" the staging simulation, despite their inability to see the instrument displays. These symptoms were slightly reduced by a change in back angle and the use of oxygen. The pilots who experienced the 15 G runs reported extreme difficulty in breathing. Speaking aloud was extremely difficult or impossible. The side-arm controller could not be moved full throw, and a loss of the sense of feel was reported. The pilots reported that it was difficult to make precise control movements at the 15 G_x acceleration level.

The pilots made ratings concerning the support system, the controller, and the panel at each of the staging acceleration levels. The ratings for the support system were consistently high up through the 15 G level. The ratings for the controller and for the panel averaged from "good" at 3 G to "acceptable" at 12 G. Ratings and interview questions used to assess the amount of physical effort and the amount of mental effort required at each of the acceleration levels indicated an increasing amount of both physical and mental effort as G increased. Similarly, more effort was required for the unstable vehicle simulations than for the stable vehicle simulations. More detailed information is given in reference (16).

In a sixth series of questions, six of the pilots were asked to estimate in percent the amount of performance decrement which they experienced at each of the peak G levels. These estimations were made when the pilots had no direct knowledge of how well they performed, and consequently, their estimations probably reflect effort, concentration, and physiological discomfort in addition to performance impairment. In all pilots, the percentage estimated impairment increased as a function of peak acceleration. Mean estimates made by 6 pilots for performance impairment were as follows: 22.5% at 6 G, 32.5% at 9 G, and 52.5% at 12 G. In making these estimations, the pilots used static tests as baselines in which 0% impairment was constant.

Figure 16 shows the mean percentage estimation of performance impairment for two pilots who completed accelerations at 1, 3, 6, 9, 12, and 15 G_x . At 15 G, the impairment estimation at peak G is 72.5%. A quantitative indication of the exact amount of error at these peaks was not possible; however, the integrated error scores which these pilots obtained during the staging runs were available. These are presented in Figure 17. The mean error for each of these four quantities did not increase as markedly as might have been expected on the basis of the estimations. Even for the 15 G staging run, the only quantity which showed any marked increase in error was yaw. Figures 16 and 17, though not directly comparable, contrast the tendency for the obtained errors to remain relatively constant (within tolerance limits) as staging acceleration increased, with the tendency for estimated performance impairment to increase as a function of increased acceleration.

PERFORMANCE WHEN DIFFERENT VEHICLES ARE SIMULATED

Studies of performance when the same pilots use the same controller under conditions in which different vehicles are simulated on the centrifuge present useful human factors data. In a recent centrifuge simulation of reentry vehicles (15, 17), the panel, seat, controller, and restraints shown in Figure 18 were used in the simulation of three basic types of proposed space vehicles. The computed aerodynamics and vehicle characteristics varied, but the piloting equipment remained constant. The controller used was Type V controller, the side-arm electronic pencil controller (15, 19). The ability of pilots to perform a series of piloting tasks was studied: maintain angle of attack, make step changes in angle of attack when deceleration reaches a certain level, maintain a constant rate of descent, change the rate of descent from its initial value to some prescribed value and hold it, level off at a certain G value, maintain zero error on the angle of attack error meter, and damp out oscillations. In general, the study showed that the procedure provided an excellent method for evaluating the ability of pilots to use the side-arm controller for performing a variety of tasks within the acceleration fields and vehicle characteristics typical of each type of simulation. Within the physiological tolerance limits, performance during centrifuge runs was not greatly different from performance on the same problems statically, even though the pilots worked harder, concentrated more, and exerted much more effort within the acceleration environments (15, 17). However, the importance of considering each performance quantity at all expected levels of acceleration was demonstrated in the experiment, and one example of this is given here. Taking a single measure of performance, such as angle of attack error, and comparing this for each of two types of vehicles at all expected levels of acceleration, it was found that differences existed

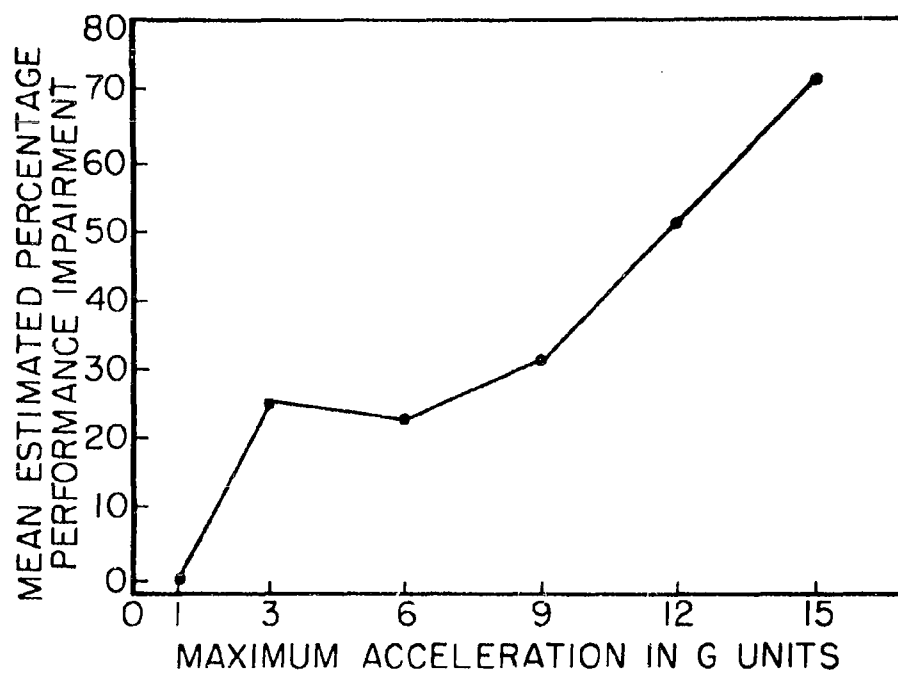


Figure 16. Mean performance impairment estimated by pilots at peak G.

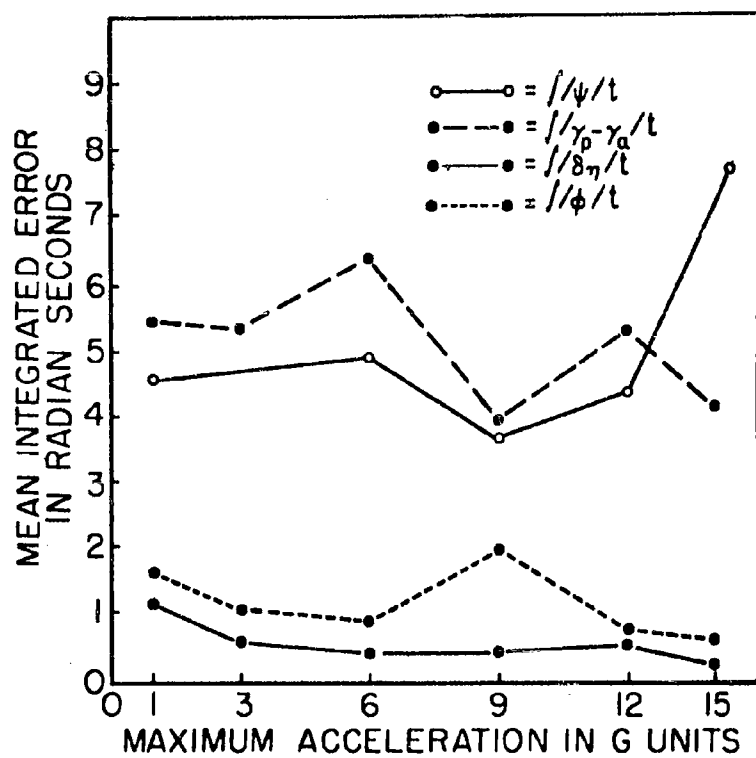


Figure 17. Mean integrated errors during staging.

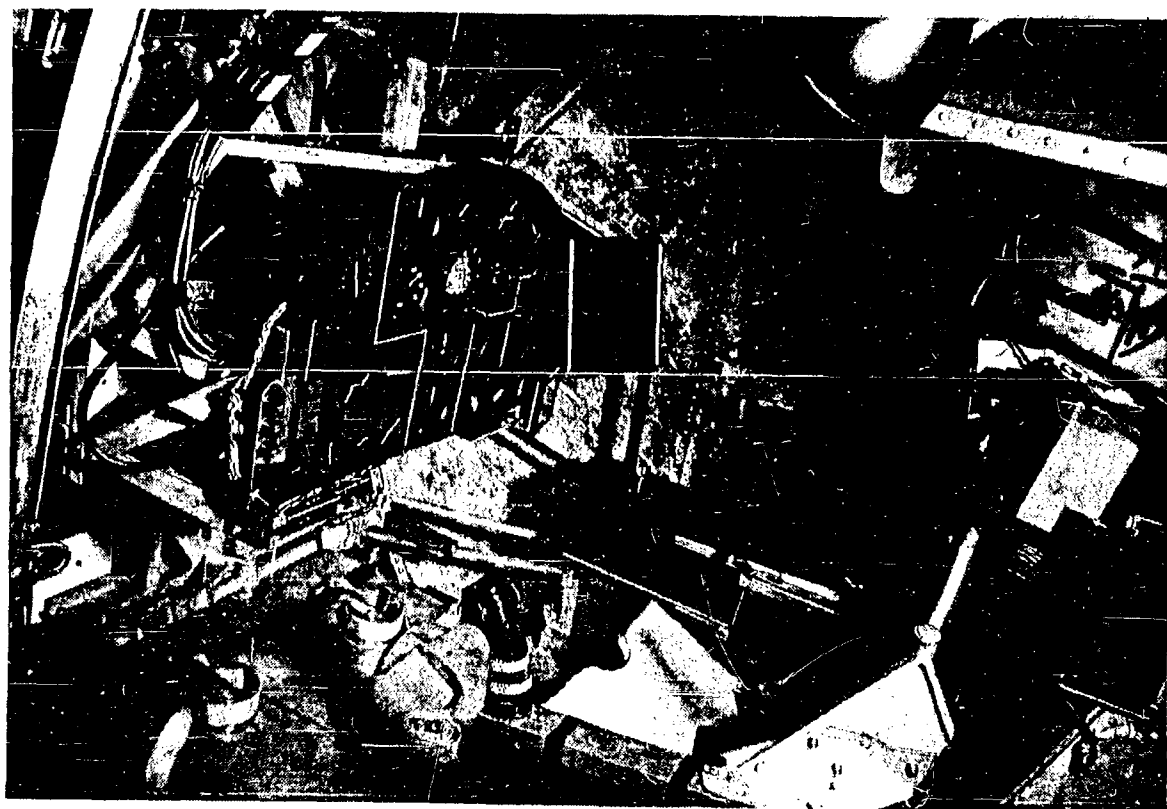


Figure 18. Installation used in centrifuge for reentry simulation experiment.

between dynamic and static (control) runs for each of two types of simulations at different points along the acceleration curve. This is shown in Figure 19 which compares integrated error accumulated by pilots who made 108 runs in two types of vehicle simulations. The graph suggests negligible differences at all acceleration levels except at the 6 G level where pilots who flew Type I vehicle made less error during static than during dynamic runs, and pilots who flew Type II vehicle made more error during static runs. However, it is important to observe that this graph does not show the results of a series of 23 pairs of runs done under static and dynamic conditions in which the pilots were able to perform the task statically, but in which they were not able to perform the task under acceleration conditions. Scores from these aborted runs could not be used in a graph such as the one above. These aborts, which had been the result of acceleration components, oscillations, inadequate head support, or excessive visual or other physiological difficulties, compose an important part of human factors data in a study of this type since they provide estimations of performance tolerance limits for using a particular control device.

In this particular program, the effects of changing stability and damping for a particular vehicle simulation under conditions of acceleration were demonstrated. In cases in which a vehicle simulation was very unstable and very poorly damped, it was generally found to be impossible to "fly" under conditions of high acceleration. An interaction effect between acceleration, side arm controller performance, task difficulty level, and vehicle characteristics was observed.

DIFFERENT CONTROLLERS FOR DIFFERENT G FIELDS

In a recent investigation conducted jointly by NASA-Ames Research Center and the U. S. Naval Air Development Center, several different types of side-arm controllers were studied in several different types of acceleration fields. The general hypothesis was that certain types of side-arm controllers could be used more effectively than others in certain types of acceleration fields. Seven different controllers were studied, designated as Types I through VII. Figure 20 shows a pilot, his special restraint equipment, contour couch and a controller within the gondola of the centrifuge. Note the special face, arm, chest, and contour couch restraint system components. These were especially designed to provide G protection along A_x , $-A_x$, A_z , and their combinations. These acceleration vectors were systematically varied in amplitude so that performance within several different acceleration fields could be tested under conditions in which each pilot used each type of controller. Figure 21 shows a typical installation of a pilot within the gondola.

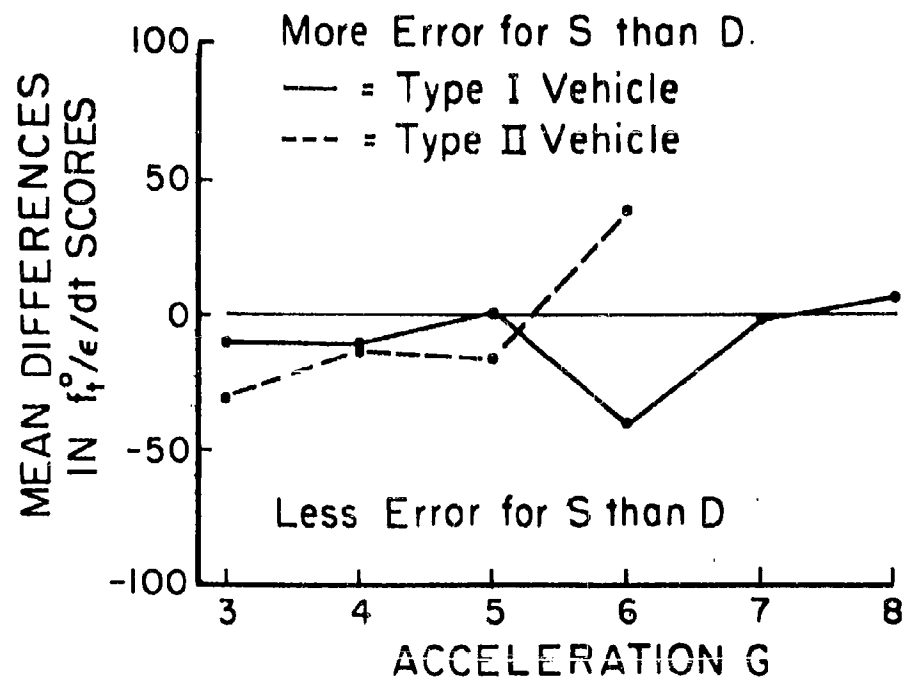


Figure 19. Differences between static and dynamic scores during simulations of two types of vehicles on the centrifuge.

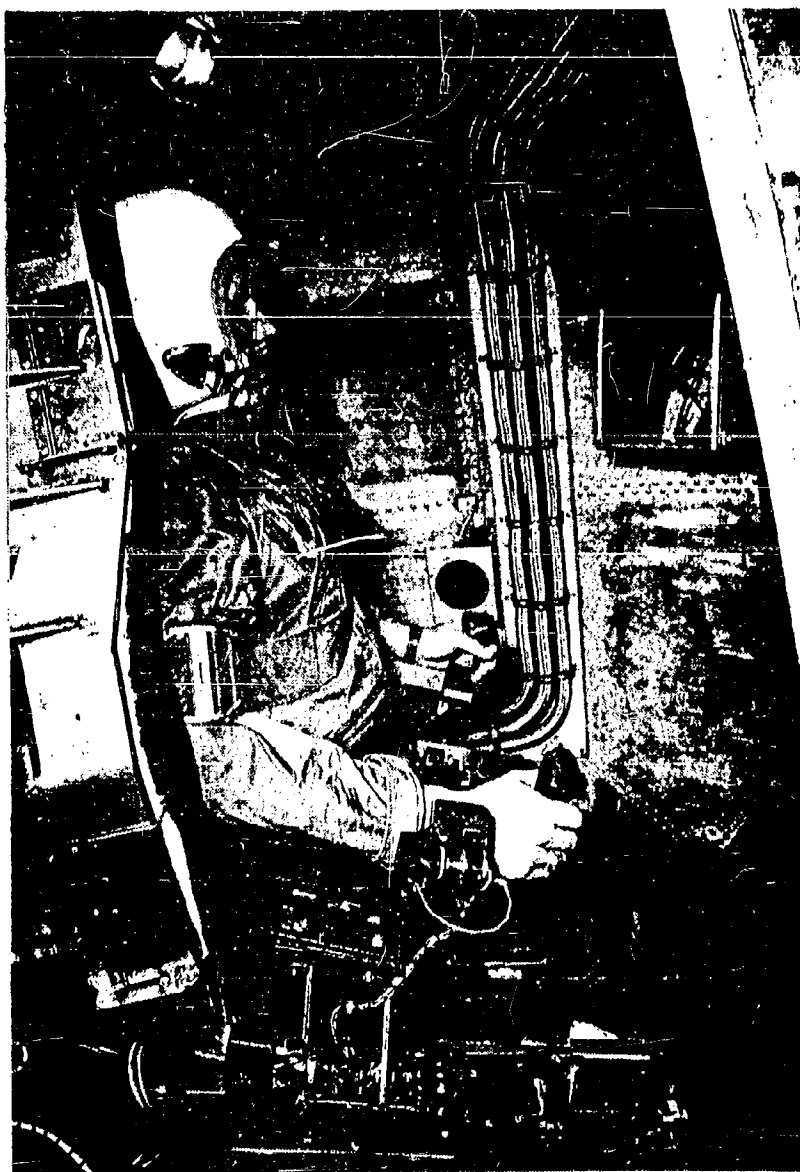


Figure 20. Typical installation used in study of side-arm control problems in varying acceleration fields.

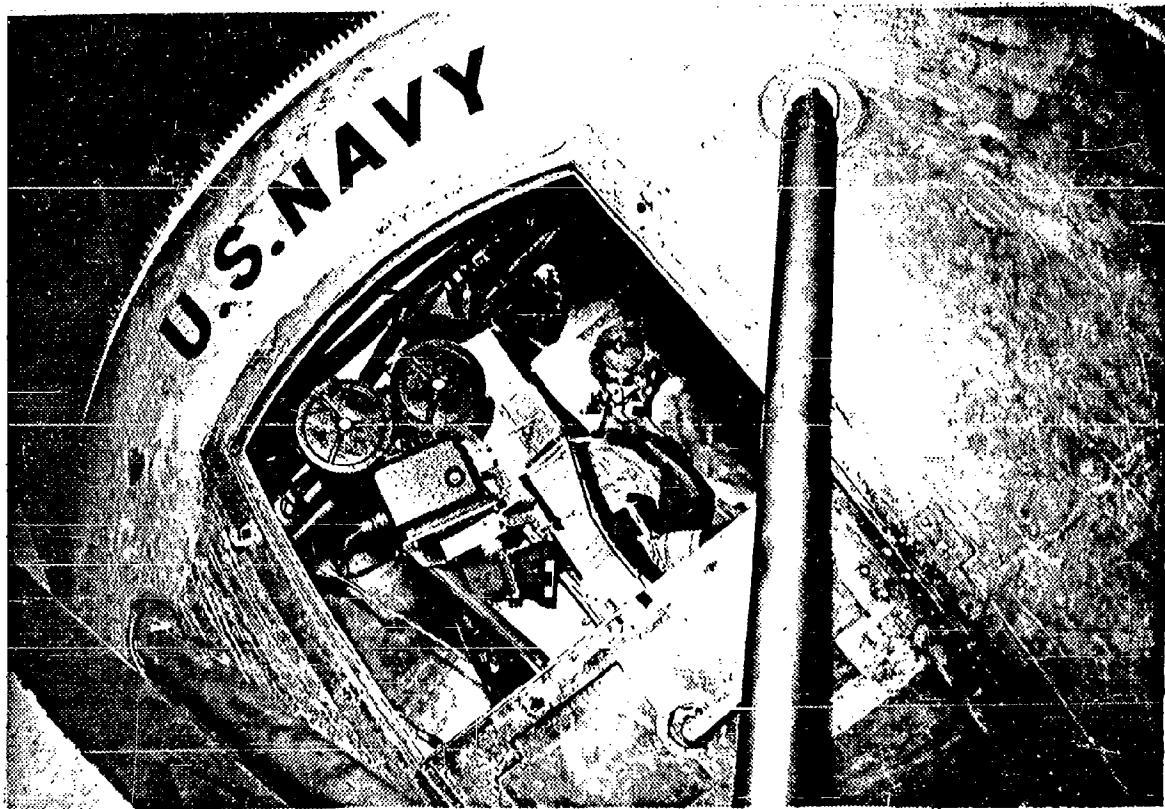


Figure 21. Pilot within gondola during acceleration run.

Controller Types I through VII were tested by pilots who performed: (a) specific flight maneuver simulations, and (b) a specific tracking task. In these tests, each pilot was brought to a specific steady G state, and then commanded to perform his piloting tasks with the centrifuge operated closed loop. Over 30 engineering, physiological, and performance quantities were recorded. In addition, piloting opinion and ratings (20) were obtained from each pilot regarding controllability and tracking performance. The display panel presented sideslip information, angle of attack, course indicator (heading), longitudinal G, normal G, and a tracking task which displayed the horizon, the vehicle, and a target, a reference line and sideslip. This same panel was used throughout the experiment. Longitudinal period and damping, and lateral-directional period and damping, were systematically varied throughout the experiment.

A detailed report is not given of the results of this experiment. However, some results will be presented to illustrate points of special interest. Figure 22, for example, has been prepared to compare mean pilot tracking proficiency scores for four test pilots who flew five types of controllers when the centrifuge was static, when the acceleration field was $+6 G_x$ by $0 G_z$, and when the acceleration field was $-2 G_x$ by $+4 G_z$. Longitudinal period and damping, and lateral-directional period and damping were constant. The piloting efficiency score (P.E.) gave emphasis to the longitudinal control task. The figure clearly shows that the Type II controller (3-axis) was characterized by lower P.E. scores than any of the other controllers. However, the graph suggests that all controllers were slightly influenced by the acceleration fields.

An analysis of the task performance in roll in these acceleration fields for the four pilots using the five types of controllers presents a somewhat different picture. Figure 23 shows the mean integrated error in roll (scored in volts as read out from the computer). Within the roll dimension, shifts in the relative amounts of error occurred when the G field changed. Type II controller was characterized by an excessive amount of roll error. However, it is noted that the least error in roll in the static condition and in the $+6 G_x$ by $0 G_z$ field was demonstrated by Type I controller, which is also a 3-axis controller. For the $-2 G_x$ by $-4 G_z$ field, the least amount of error in roll appeared to be in Type III controller, which was Type I with the yaw dimension locked on the side-arm controller and placed in "toe" pedals operated by the feet.

Using the 10-point rating scale developed by Cooper (20), the pilots evaluated general controllability and tracking. Ratings for four controllers at two levels of longitudinal and lateral-directional dynamics are shown in Figure 24. These are average ratings, based on four pilots. These ratings

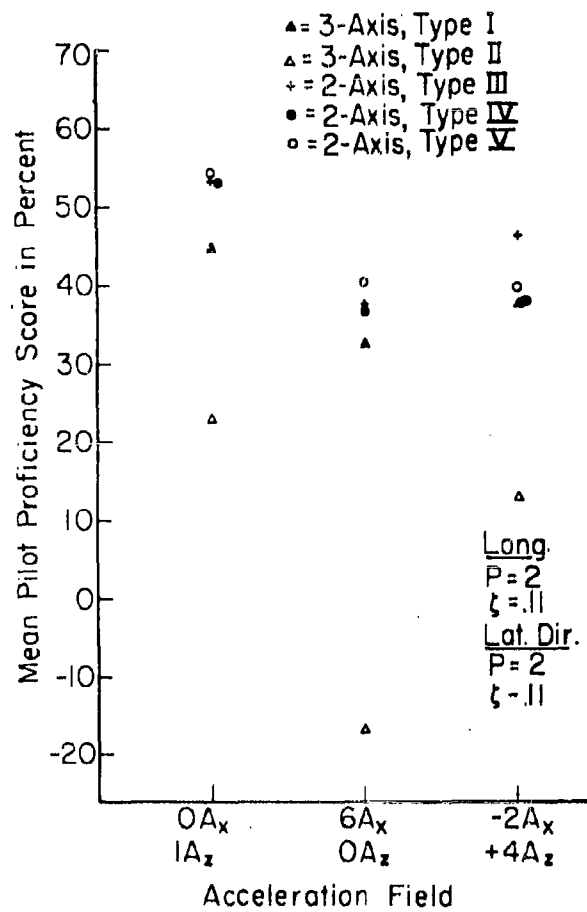


Figure 22. Mean pilot efficiency scores in different acceleration fields.

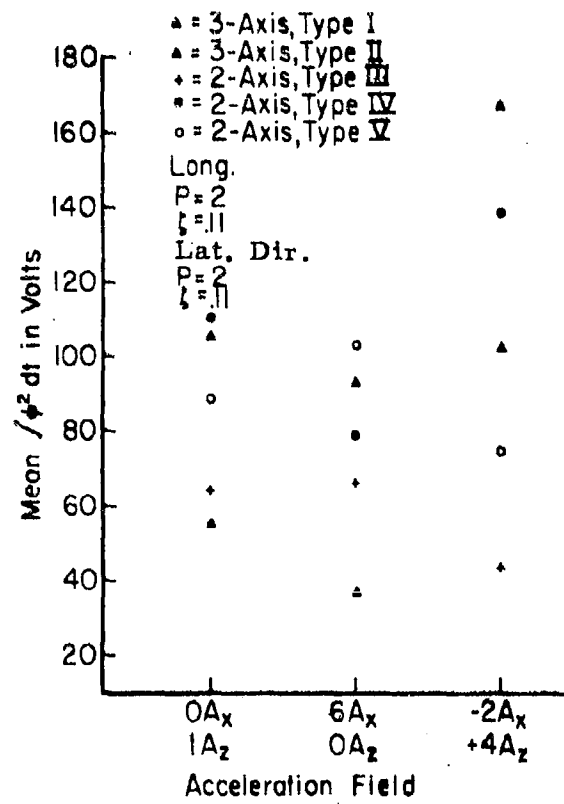


Figure 23. Roll error scores for pilots who performed a tracking task within several acceleration fields.

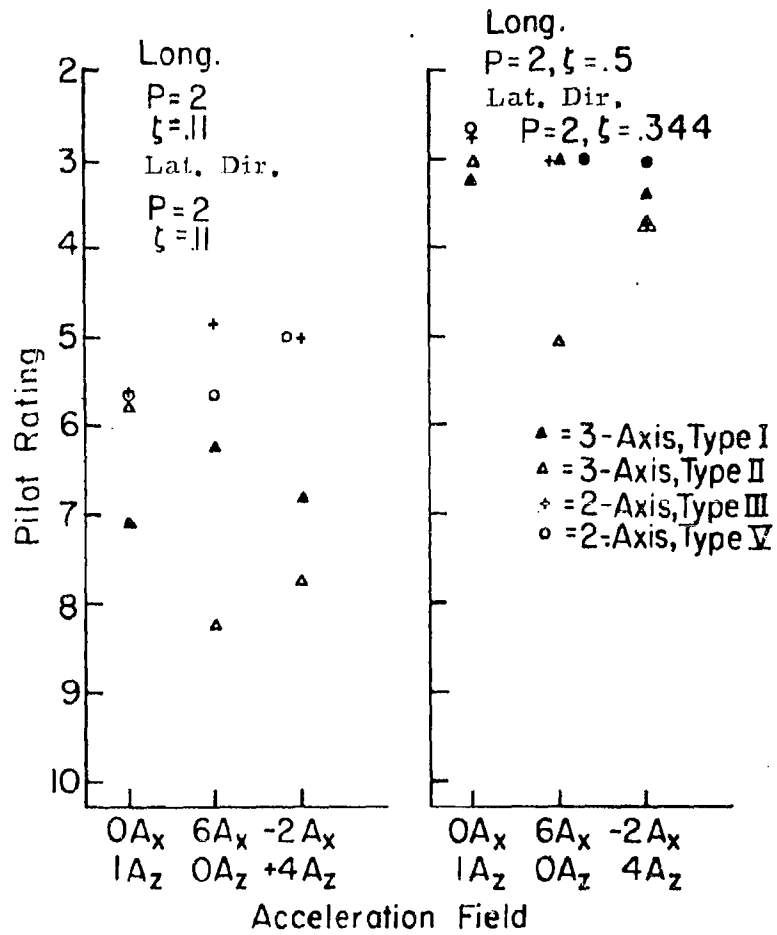


Figure 24. Mean pilot ratings of vehicle controllability in conditions in which they used several side-arm controllers.

appear to agree in general with the obtained measurements of error, and of piloting efficiency. When the characteristics of the vehicle simulation were improved, a general improvement in all ratings also occurred, as is shown at the right side of the graph.

Figure 25 shows the mean integrated error scores in pitch and roll for performance on each of four types of controllers within two acceleration fields. These scores are in terms of volts as read out on the computer and, therefore, direct comparisons in amplitude should not be made between pitch and roll. The figure illustrates that pitch error was approximately the same for all controllers in the $+6 G_x$ by $0 G_z$ field, whereas in the $-2 G_x$ by $+4 G_z$ field, pitch error for one controller (Type II) was markedly increased, but not in the other three. Inspection of the roll error scores suggests specific superiority of some controllers over others for the $+6 G_x$ by $0 G_z$ field. In the $-2 G_x$ by $+4 G_z$ field, a shift in the relative rankings of the controllers according to the amount of error is observed.

On the other hand, some controllers may show little, if any, detectable differences as a function of the acceleration fields in which they are immersed. For example, Figure 26 compares the piloting efficiency scores for 5 pilots who flew the same flight problem in three different types of G fields, $-5 G_x$ by $0 G_z$, $0 G_x$ by $+1 G_z$, and $+6 G_x$ by $0 G_z$. Type VI is a hand force grip controller, and Type VII is a finger force grip controller. The error differences shown in this graph were very small and were not significant.

PERCEPTIONS REPORTED WITHIN DIFFERENT G FIELDS

In a second phase of the study, five pilots were asked to rank in order of physiological difficulty a series of acceleration fields to which each pilot had been exposed and within which he had performed piloting tasks. A total of 21 series of ratings were included in this analysis. The results of this analysis are presented below. The G fields are ranked in order of physiological difficulty. The first field is the easiest, according to the analysis and the last field is the most difficult. To obtain the relative order of these fields, the mean rankings for all pilots for all fields were used as the criterion.

Acceleration Field

<u>A_x</u>	<u>A_z</u>
. 0	by +1
-3	by 0
0	by +4
-4	by 0
+5	by 0
-5	by 0
-6	by 0
+6	by 0
0	by +5

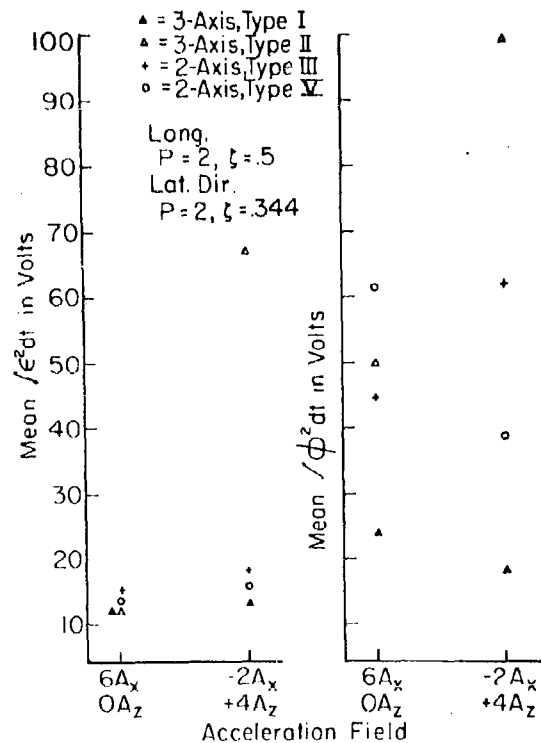


Figure 25. Mean error scores obtained during tracking. Longitudinal and lateral-directional dynamics were held constant.

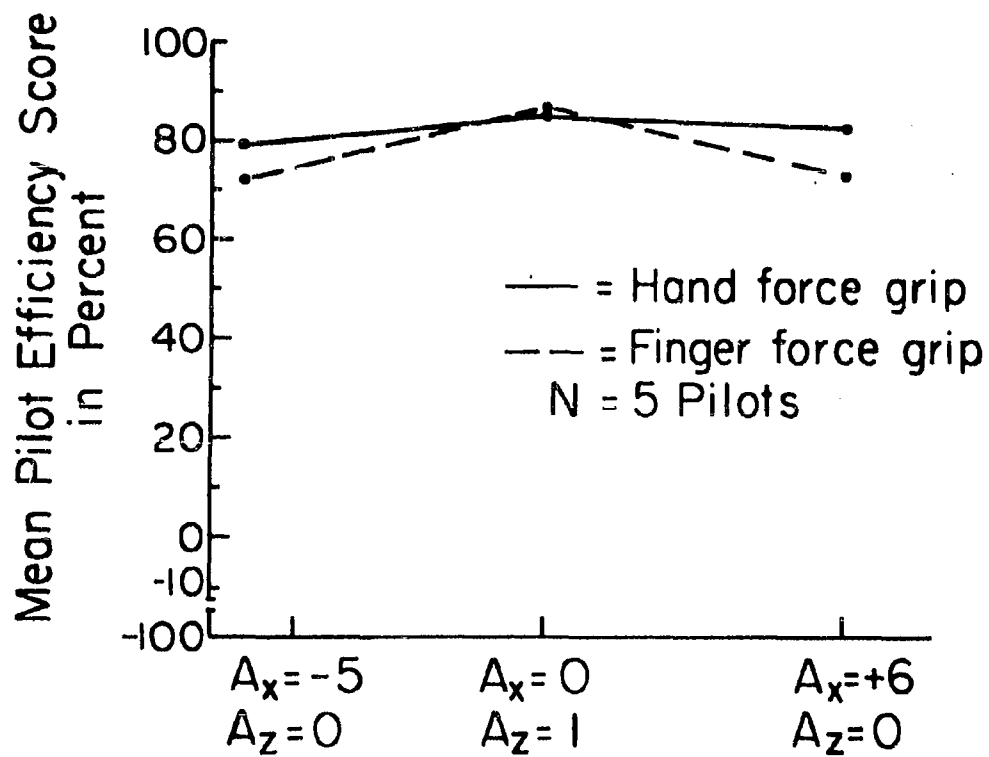


Figure 26. Pilot efficiency scores for 5 pilots who operated a hand force grip controller (Type VI) and a finger force controller (Type VI) in three G fields. Longitudinal and lateral-directional dynamics were held constant.

The exposure time for most of these runs was 2 1/2 minutes, although some were as short as two minutes, and some were as long as 7 minutes. The pilots were fully conscious in all cases, enduring the discomfort of the centrifuge run and in control of the simulated vehicle.

A content analysis of piloting opinion, answers to standard questions, and interview data, was made to summarize pilot perceptions reported for each type of run. In the $0 A_x$ by $+A_z$ acceleration field there were sensations of pain in the lower legs and in the toes, and feelings of swelling and fullness in the lower extremities. There was a marked tendency to grey out, accompanied by a considerable amount of discomfort due to the G suit which the pilots wore. In this G field, the operation of "toe" pedals required additional effort and concentration. There were also some breathing difficulties. Effort was necessary to make control motions of the hand in an upward direction (pitch) to overcome the force of gravity. The primary sensations which pilots experienced along the $+A_x$ by $0 A_z$ vectors were restriction in breathing, pressure on the chest accompanied by some chest pain and difficulty in breathing. Additional effort was required to make forward motions of the limbs. In the $-A_x$ by $0 A_z$ acceleration field, the pilots reported fullness of the face and thigh, pooling of blood in the hands and feet (frequently accompanied by pain), and pressure points along the chest and face supports. The eyes appeared to extend outward. Breathing was easier in this field than in the other two fields. Vision was frequently blurred. In the $+A_x$ by $+A_z$ acceleration field, tingling in the toes and feet, sometimes accompanied by pain, and feeling of stiffness in the lower extremities occurred. There was also a slight blurring of vision.

DISCUSSION

In the three closed-loop centrifuge experiments reported in this paper, the pilots usually performed as well, and sometimes better, under acceleration as they did statically. There were exceptions, however, and these occurred under the following conditions: (a) centrifuge simulations in which the acceleration stress was at or in excess of the physiological tolerance limits of the pilot, (b) simulations in which the pilot was exposed to acceleration stress for a relatively long period of time, and (c) simulations in which the controller and/or vehicle dynamics were not appropriately adjusted for certain types of acceleration fields. Despite discomfort, breathing difficulties, visual impairment, and pain, the pilots in each of the three experiments were capable of maintaining control of their simulated vehicles under conditions of adverse acceleration stress. The pilots were able to compensate for physiological discomfort and for deficiencies in side-arm controller design. During the acceleration tests, the pilots

found it necessary to exert much more effort than was necessary under static conditions. They were more highly motivated during the acceleration runs than during the static runs, the centrifuge offered a more realistic task when in motion than when static, and the closed-loop centrifuge acceleration conditions offered more unpleasant consequences for inadvertent control inputs and related piloting error. When transients, instability, and poor damping were provided, the acceleration conditions offered even more challenge, and the pilots demonstrated high degrees of concentration and piloting effort, and a willingness to tolerate pain in order to perform the piloting task.

Whereas the data presented in this paper have been largely integrated error quantities for portions of the piloting performance, it should be emphasized that detailed analysis of the individual recordings and reactions of any given pilot for any given run should always precede the analysis of data obtained from groups of subjects. Whereas in the present report several group trends have been suggested, these should be regarded as tentative, because it is felt that sufficient data have not been obtained to support any specific conclusions about side-arm controllers for specific acceleration fields. Additional testing involving larger numbers of subjects with more trials under each conditions will be necessary. Also, it should be emphasized that the pilots tested in these experiments were a highly select and trained group, and it is not felt that they represented a population of subjects from which generalizations could be drawn without bias.

For the engineer who is concerned with the design and test of a side-arm controller, it is important to take into consideration the controller characteristics which are susceptible to change under conditions of acceleration. The criterion which is most helpful is to consider the characteristics which the pilot perceives as changing when he is attempting to perform control operations under static conditions and under the specific acceleration conditions for which the controller is being designed. Below are listed eleven controller characteristics which have been observed in these closed-loop centrifuge experiments to be especially susceptible to change when a pilot is performing a task in varying acceleration environments.

1. stick force gradients along each mode of control
2. centering characteristics along each mode of control
3. break-out force
4. control friction
5. damping characteristics
6. control throw
7. control response time
8. control harmony
9. cross coupling
10. control feedback
11. control sensitivity

In the design and test of a controller, the engineer should consider both the physiological characteristics of the pilot and the physical force characteristics of the controller which may change as a function of acceleration. For some types of acceleration fields, it may be necessary to consider the restraint system for the pilot, the position of the controller with respect to the pilot, and the number and location of the axes of motion with respect to the pilot and the acceleration field. The ability of trained pilots to use the proposed controller in performing specific piloting tasks within the expected acceleration environments should then be tested as early as possible in the design phase.

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1. Report NADC-MA-6110
2. Subtask MR005.13-0005.6
Problem Assignment
J04AE13-7

U. S. NAVAL AIR DEVELOPMENT CENTER, JOHNSVILLE, PA.
AVIATION MEDICAL ACCELERATION LABORATORY

Control Performance Under Acceleration with Side-Arm Attitude
Controllers: by Randall M. Chambers, Ph.D., 27 November
1961, 43 pp.

This paper presents some procedures, data, and conclusions based on several closed-loop centrifuge experiments in which side-arm controllers were used by pilots to perform specific control tasks. Under certain conditions the pilots could perform as well in adverse acceleration fields as they could statically, even though they were exerting much more physical effort and psychological concentration, and they were enduring visual impairment, chest pains, breathing difficulties, and other stressful effects of acceleration. The pilots demonstrated a remarkable ability to adapt to physiologically severe acceleration environments, and they maintained control performance within acceleration time history profiles which contained vectors with amplitudes as high as $+15 G_x$, $-7 G_y$, and $+7 G_z$. Some closed-loop human centrifuge simulations were conducted which provided human factors data which may have application to the design and evaluation of side-arm controllers for use within proposed space vehicles.

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